

Identification and modeling of the manufacturing impact due to laser cutting on magnetization behavior employing ring shaped soft magnetic steel specimen

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The presented paper focuses on the influence of manufacturing, i.e., laser cutting, on the magnetic behavior of soft magnetic steel sheets. A material degradation model (MDM) on the basis of an analytical eddy current (EC) model is introduced, and the corresponding identification routine is presented. For the model parameter's determination ring shaped specimen (RS) in two different material grades, cut with two different laser cutting techniques, in five different geometries respectively are characterized for their magnetization behavior. Furthermore, to verify the results wire eroded samples, unaltered in their magnetic properties, are utilized as reference. Moreover, scanning electron microscopy (SEM) is employed to investigate the changes in the material's micro-structure, as well as a verification for the modeling results.

Index Terms—Computational modeling, Degradation, Loss measurement, Magnetization, Soft magnetic materials

I. MOTIVATION

BEFORE soft magnetic materials (SMM), in the form of electrical steel sheets, are employed in electric machines, such as induction motors, they have to pass through a series of manufacturing steps, e.g., cutting, stacking, housing. With each subsequent step, the magnetization properties, such as permeability or specific iron losses, are changed. When neglected, this alteration leads to inaccuracies in the design process of electric machines, and is therefore a research subject picked up in recent times [1,2,3]. This paper will focus on the influence of cutting, in particular by means of laser, on the magnetization properties of SMMs. The laser cutting process leads to rapid heating and cooling of the SMM near the cutting edge and is cause to thermal stresses inside the material. These stresses entail micro-structural changes close to the edge, resulting in a decrease in permeability, while the specific iron losses increase. Accurate identification and modeling of this effect contributes to improving the accuracy of the design process of electrical machines.

The full paper will present electromagnetic measurements, an analytical material degradation model (MDM) including an identification routine, as well as a measurement based verification of the modeling results.

II. METHODOLOGY

The methodology applied is now explained in abbreviated form. First, the laser cut SMM's degradation is characterized. This is performed by the means of ring shaped samples (RS). Since the measurement routine according to IEC 60404-6 only yields integral magnetic quantities, the RS widths are varied. This variation in ring width yields a difference in the integral magnetic properties, and, therefore, the possibility to identify the local magnetization behavior near the cut edge. Five different RS geometries are manufactured using CO₂ Laser, as well as Fiber Laser (FL). To acquire the unaltered magnetic

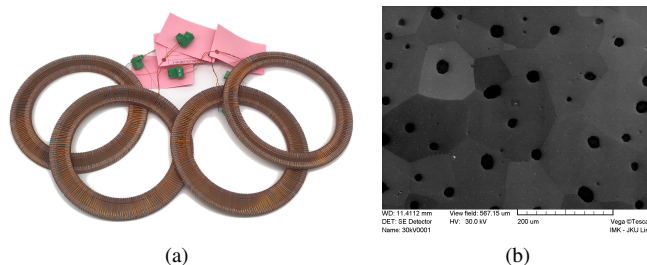


Figure 1. (a) Ring shaped samples (RS) wound with a primary and secondary coil for electromagnetic characterization, and (b) micro-structural analysis of a specimen, using scanning electron microscopy (SEM) with a secondary electron (SE) detector.

properties of the SMM, wire eroded (WE) samples are used as a reference, since wire eroding is known to influence the magnetization behavior the least [4]. Additionally, for each RS at least one parallel sample exists, in the event of intentional or unintentional destruction of the RS. Intentional destruction has to be performed for some of the RS to investigate the laser's influence on the micro-structure and magnetic domains using scanning electron microscopy (SEM), utilizing both secondary electron (SE) and back-scattered electron (BSE) detectors. The knowledge gained via SEM is also used to verify the modeling result acquired later on. With two different material grades (NO27-14 and M250-35A) at hand, a total number of 54 samples are available as a foundation for the following modeling, parameter identification, and verification work flow.

Next, an analytical eddy current (EC) model [5] in combination with a parametric MDM is employed. The MDM alters the permeability as well as iron loss coefficients in dependency of the distance to the cutting edge, while the EC model accurately reflects the frequency dependency of the materials internal magnetization state. The MDM's parameters are identified using measurement data acquired with damaged,

laser cut RS. Subsequently, the undamaged, wire eroded RS, are used to verify the identified intrinsic electromagnetic material parameters, i.e., electrical conductivity and magnetic permeability. Furthermore, the determined damaged zone's width can be verified using the results obtained through SEM investigation.

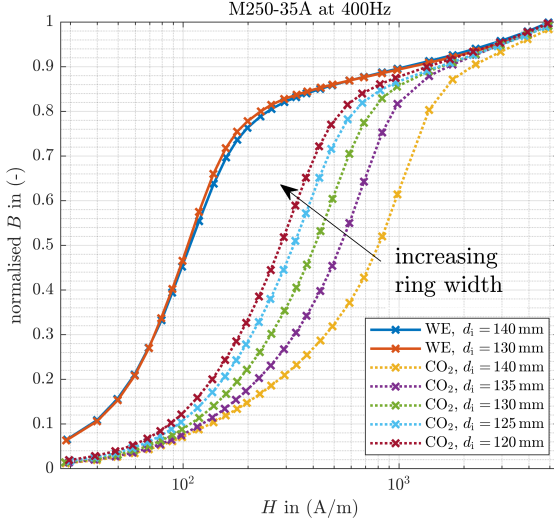


Figure 2. Measured magnetization curves for CO₂-Laser cut M250-35A samples, as well as wire eroded (WE) samples, with fixed outer diameter $d_o = 150$ mm and varying ring widths, at an excitation frequency of $f = 400$ Hz.

III. PRELIMINARY AND EXPECTED RESULTS

Preliminary electromagnetic measurements of the damaged and undamaged RS show a clear dependency of the integral magnetic properties on the ratio of damaged to undamaged material volume, further reflected by analyzing different ring widths. Figure 2 shows the normalized BH-magnetization curves for the M250-35A samples, cut by the means of CO₂ laser and wire eroding, at a frequency $f = 400$ Hz. While the outer diameter is the same for all samples ($d_o = 150$ mm), the inner diameter d_i varies between 120 mm to 140 mm. According to theory, the narrowest sample (CO₂, $d_i = 140$ mm) shows the worst magnetic properties, while the widest sample (CO₂, $d_i = 120$ mm) is influenced the least by material degradation due to the cutting process. This trend can clearly be observed in the illustrated magnetization curves plotted in Fig. 2. As discussed, the magnetic properties of the wire eroded samples (WE) show no significant dependency on the sample's width, backing up the claim that wire eroding leads to no remarkable material degradation.

In Fig. 3, an exemplary magnetization state calculated by the means of the analytical EC model and the MDM is presented. At the top of Fig. 3, the H -field weakening inside the ring's cross section due to EC is clearly recognizable. The middle plot depicts the resulting flux density without consideration of material degradation, i.e., undamaged material, while at the bottom of Fig. 3 the permeability in proximity of the radial edges is decreased via the MDM, yielding a lower flux density at the cut edges of the material, and, therefore, a decrease of the overall integral B -field.

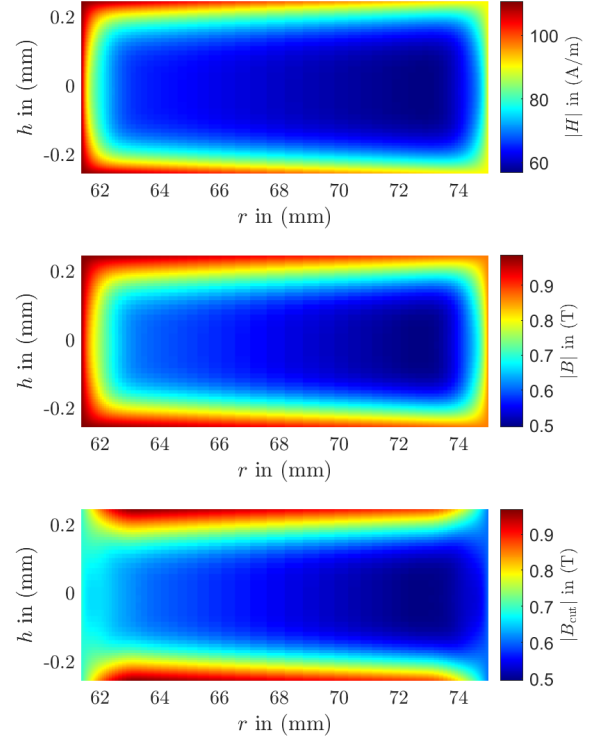


Figure 3. Exemplary spatial distribution of the magnetic field quantities calculated with an analytical eddy current (EC), over height h and radius r of the sample's cross section, at a frequency of $f = 400$ Hz: (top) magnetic field strength, (middle) resulting flux density without consideration of material degradation due to laser cutting, and (bottom) flux density altered by a material degradation model (MDM) near the radial (r) edges of the sample resulting in B_{cut} .

IV. OUTLOOK

In the final conference contribution, the aforementioned investigations are presented in more detail. Further electromagnetic characterization results showing the general validity will be given. The mentioned analytical models as well as the parameter identification work flow is introduced in detail. Lastly, the verification results by means of WE reference samples and SEM investigations are unveiled.

V. ACKNOWLEDGMENT

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